RFID Array Sensing

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***Abstract*—In this paper the use of RFID tags for the measurement of physical parameters in a distributed set of points is presented. Experimental results for two different scenarios are presented; the first uses a 2D RFID array to measure the field distribution of a radiating aperture, while the second detects the change in the close environment of an array of RFID tags to determine the water level of a container.**

I. Introduction

There is a growing need for small sensors able to measure and deliver accurate information about the physical parameters inside or around complex media. Different Industrial, Scientific and Medical sensing and imaging applications rely on these measurements to extract information about the scene under test. In order to improve the usability of such sensors, they need to be as low invasive as possible in their scenario, so that they become transparent. Therefore their first requirement is that they need to be as small as possible. The next requirement concerns its power supply. Basically two possibilities arise for embeddable sensors, either they have a battery that feeds its circuitry, active sensors; or they are powered externally through an scavenging scheme, self-active/passive sensors. A third solution can be envisioned, where the sensor does not require a power source at all [1]. The third basic requirement is the communication of the measured data to the reader. To preserve as much power as possible, to ensure long-life of the sensor, the best option is a passive transmission of the data, without an actual supply of energy from the power source of the sensor to the antenna. A backscattering solution meets this requirements.

Radio Frequency Identification (RFID) technology [2] complies with the previous requirements, and thus is an excellent starting point for sensing probes. RFID sensing capabilities have been exploited in two main directions. Some groups have followed a direct approach consisting in the enlargement of the concept of RFID [3]–[5], adding to the RFID IC circuitry that includes sensors that encode their measurements as part of the RFID memory banks, and thus sendings back through the conventional RFID response the desired information. Other groups have focused on exploiting the fact that the RFID tag antenna is affected by the conditions of the media in which it is immersed. Therefore, the response measured by the reader will be affected by changes on its input impedance [6]–[8] .

This conference paper presents the work that we have performed on the indirect approach to exploit sensing capabilities using arrays of RFID tags. Two experimental results will be presented: the measurement of a 2D field distribution, and the 1D measurement of the level of liquid in a container.

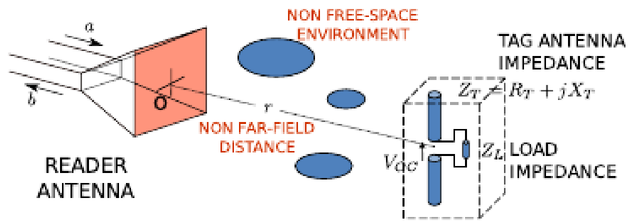


Fig. 1. General scenario of RFID scenario, with a non-line of sight and scattered present between reader and tag

II. Embedded RFID-tag Backscattering Analytical Formulation:

Data communication between the reader and the RFID tag operate in a backscattering mode where the RFID tag switches between two loads (Z_{L1} and Z_{L2}) modifying the way it scatters the incoming energy, and thus modulating it so that it can be received by the reader. This technique is known as backscattering modulation. Such a modulation mechanism can be modeled under free-space and far-field assumptions [9], or more generally using a reciprocity based formulation [10] which allows to study any scenario, such as the one depicted in Fig. 1. With this formulation, the differential response of the tag measured by the reader can be expressed as:

$$\Delta\rho_T = \frac{Z_{tr}}{2R_T}\left(\tilde{\rho}_{L_1} - \tilde{\rho}_{L_2}\right) = \frac{Z_{tr}}{2R_T}\Delta\tilde{\rho}_L \tag{1}$$

where R_T is the tag antenna input resistance, $\tilde{\rho}_{L_1}$ and $\tilde{\rho}_{L_2}$ are the complex reflection coefficient of the tag for each of the two loads, and Z_{tr} is the transfer impedance:

$$Z_{tr} = \frac{V_{OC}^2}{2P_a} \tag{2}$$

where V_{OC} is the open circuit voltage at the tag antenna, and P_a the power at the reader. From eq. (1), the component $\frac{\Delta\tilde{\rho}_L}{R_T}$ is directly affected by any changes in the tag antenna impedance (Z_T). Thus any variations of the near environment permittivity will affect the measured response.

For the remaining part considering the definition of the transfer impedance, (2), and relating V_{OC} to the incident field through the effective length of the tag antenna (h_{ef}), the following complete expression may be obtained showing the simultaneous dependence of the backscattered field on the incident field on the tag antenna and on the tag antenna impedance:

$$\Delta\rho_T = \frac{V_{OC}^2}{2P_a}\frac{1}{2R_T}\Delta\tilde{\rho}_L = \frac{E_{inc}^2 h_{ef}^2}{2P_a}\frac{\Delta\tilde{\rho}_L}{2R_T} \tag{3}$$

III. Array sensing

A set of RFID tags can be used to obtain simultaneous information from several locations. Taking into account (3), each of the measured values can be related either to the changes into the incident field or to the changes into the local environment physical parameters. For instance [11] shows the capabilities of a single moving RFID tag to retrieve the field distribution and [8] shows the effect of a change in the permittivity of water, due to an increase of temperature, in the measured response of the tag. The latter can be characterized and used to monitor the changes in temperature. In this paper we present two different experiments of sensing applications with RFID arrays. The first one studies the capability of measuring the incident field distribution on a 2D grid of points, for a uniform physical scenario. The second one investigates the capability of measuring the changing physical parameters on a 1D grid of points that are illuminated by a known incident field distribution.

A. Near-Field Distribution Measurements with an array

In (3) the dependence of the measured response of the tag with the incident field on it is clearly noted. Moreover, the authors already presented in previous conferences the possibility to use RFID tags to measure the near-field distribution of horn antenna, [11], [12] . In these works a single element was moved along a line in order to retrieve the field distribution. Nevertheless in many cases the possibility of moving the probe in the scanning area, is somewhat limited, or even impossible for embedded sensors. In this cases the use of an array configuration is able to perform the measurement. In this section we will discuss how this array can be configured, and what are the trade-offs that can be used when using an array of RFID tags.

To obtain an accurate representation of the near-field distribution, it is necessary to at least obtain a spatial distribution with a $\frac{\lambda}{2}$ sampling step , also it is necessary that the measurement probes are not influenced by the scattered field of nearby probes, thus low coupling between probes is desirable.

Since RFID field measurement follows the same principle than the Modulated Scatterer Technique (MST), a similar procedure can be followed to study the influence of each term [13]–[15]. Fig. 2 presents a circuital representation of the measurement system of N RFID probes. Each of the probes is loaded with a given impedance load ($Z_{L_i}^a$, with a being the scavenging ($a = A$) and modulating states ($a = B$), with the scattering matrix relating the port as:

$$\underline{b} = \underline{\underline{S}} \cdot \underline{a} \tag{4}$$

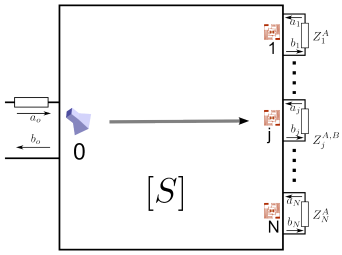


Fig. 2. Array of N RFID probes being interrogated by a reader, and equivalent circuit with N+1 ports, to be characterized with scattering matrices

where $\underline{b}$ and $\underline{a}$ represent respectively the outward and inward power waves at each of the ports. Considering that ports $i = 1..N$ are loaded with a given impedance (Z_{L_i}), and assuming perfectly matched generator on port 0, we can define the reflection matrix at the ports, $\underline{\underline{\Gamma}}_L$ as:

$$\underline{\underline{\Gamma}}_L = diag\left(0, \rho_{L_1}, \rho_{L_2}, \ldots, \rho_{L_N}\right) \tag{5}$$

where $diag$ represents a diagonal matrix, and ρ_{L_i} is the reflection coefficient ($Z_o = 50\Omega$) of the load at port i. Taking this representation into (4) and rearranging, $\underline{b}$ can be found as:

$$\underline{b} = \left[\underline{\underline{I}} - \underline{\underline{S}} \cdot \underline{\underline{\Gamma}}_L\right]^{-1} \cdot \underline{\underline{S}} \cdot \begin{pmatrix} a_o \\ 0 \\ \vdots \\ 0 \end{pmatrix} \tag{6}$$

the measurement at the reader is then $\rho_T = \frac{b_o}{a_o}$. For the measurement of the response of tag j, the tag IC switches between two different states, $\rho_{L_j}^{A,B}$, while the rest of the tags ($i \neq j$) remain at the scavenging states, $\rho_{L_i}^{A}$.

The previous equation can be particularized for an array of 2 RFID elements to present a clear understanding of how each of the terms may affect the measurement. If we consider tag $i = 2$ as the transmitting tag, changing from state A to B, after some development $\Delta\rho_T$ is found as:

$$\Delta\rho_T = \frac{\Delta\tilde{\rho}_{L_2}}{2R_{T_2}} \cdot \frac{Z_{T_2} + Z_o}{2Z_o} \cdot \left[S_{o2} + \frac{S_{12}\rho_{L_1}}{1 - S_{11}\rho_{L_1}} S_{o1}\right]^2 \tag{7}$$

where Z_{T_2} is the input impedance of tag 2 and Z_o the characteristic impedance of the scattering parameters. Eq. (7) shows the dependence of the measurement with the array configuration. Although Z_{T_2} and therefore $\Delta\tilde{\rho}_{L_j}$ are affected by the elements of the array, through the mutual impedances, the term is multiplicative, and thus once the array has been designed and constructed it remains constant, its value is independent of the incident field distribution, therefore the dependence can be removed by a calibration/normalization procedure [16]. Nevertheless, the second term of (7) shows that $\Delta\rho_T$ is dependent with S_{o1} and S_{o2}. The latter contains the field distribution of interest, the one at the probe point 2, while the term dependent of S_{o1} is an undesired component, that depends on the field at the probe 1. It must be ensured that the term $\frac{S_{12}\rho_{L_1}}{1-S_{11}\rho_{L_1}}$ is low enough that for the dynamic

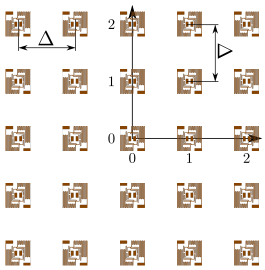


Fig. 3. Arrangement of the 5x5 array of RFID tags. The spacing between elements is changed to study the effect of the coupling effect through simulations

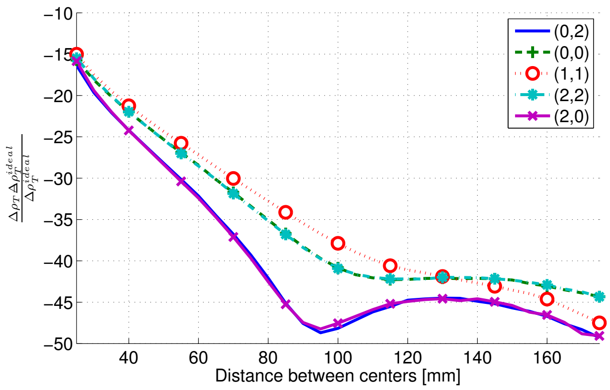
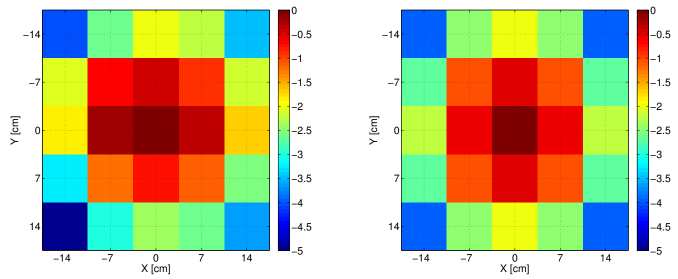


Fig. 4. Evolution of the error in the measurements for different spacings. The measurement considers uniform S_{oi} for the whole array expect for the measurement point which is $10dB$ below



(a) Measurement (b) Simulation

Fig. 5. Magnitude of the measured field distribution at a distance of 25cm from the aperture of the horn antenna (a) compared with the near field simulated using the MoM (b)

range of the field distribution to be measured ($\frac{S_{o2}}{S_{o1}}$) the error introduced does not degrade the measurement accuracy.

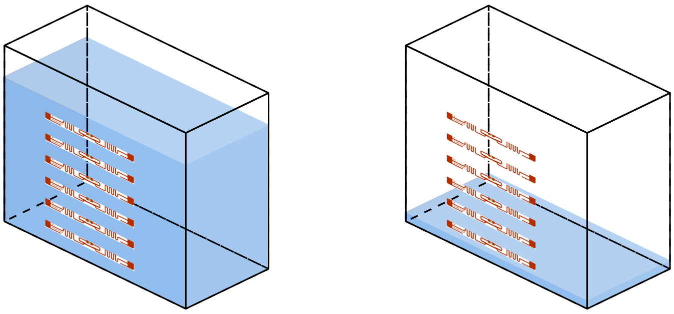
1) Mutual coupling of a 5x5-element array: Fig. 3 presents an array of 25 elements based on the Alien ALN-9529 Squiggle-SQ tags. The coupling between elements can be controlled by modifying the distance between the elements. The array has been simulated with MoM considering a uniform spacing (Δ) between elements in both directions. After obtaining the scattering matrix for different spacings, they have been introduced in equation (6), using $Z^A_{L_i} = 15 - j150$ and $Z^B_{L_i} = 0$ as the scavenging and modulating loads respectively to obtain the measured response. Fig. 4 presents the error in the measurement for different probes as a function of the spacing between elements. In the evaluation, a uniform field distribution is considered upon the different elements of the array. It is observed that the error decreases as the spacing increases. For $\Delta = 70mm$, the error is about $30dB$ below the measurement, for a uniform field distribution.

2) Experimental results: The array of fig. 3 has been constructed, using a separation between elements $\Delta = 70mm \quad (\frac{\lambda}{5})$, to ensure that the errors on the measurement due to coupling effects are minimized. The array is placed on a 2D linear stage at a distance of $25cm$ from a ridged horn antenna with an aperture of dimensions $19cm \times 27cm$. The measurement setup consists of a Rohde&Schwarz SMJ100A vector signal generator that generates the proper protocol for activation of the RFID tags, and a Rohde&Schwarz FSL6 spectrum analyzer which can coherently acquire the I/Q components of the reflected signal. In order to retrieve meaningful values of the field using RFID probes, due to the non-linear behavior of the RFID IC input impedance [17], it is necessary to characterize the power response of each of the tags, and apply the proper correction to the measurement, [18]. The power characterization is done with the help of the 2D linear stage, by properly moving each of the tags to the same reference position. Fig. 5 presents the measured field distribution when the array is centered in front of the aperture. The same figure also presents the expected field distribution, obtained by a simulation based on the MoM.

B. Multi-point Environmental Change Measurement

It is well known that when an antenna is immersed in a liquid, the permittivity of the surrounding medium influence directly its input impedance. In the principle of operation of RFID tags, this has two direct consequences. At one hand, the change in input impedance introduces a modification of the term $\frac{\Delta\tilde{\rho}_L}{R_T}$ and thus in the measured response at the reader. On the other hand, the change of input impedance will decrease the matching between the antenna and the IC scavenging load; if the mismatching is too large, the tag does not get enough power and thus will not be able to activate. Both effects can be exploited in order to detect variations of the effective permittivity of the neighborhood of the tag antenna, [6], [8], nevertheless the first one is more robust in terms of false detections, since it always receives an answer from the tag.

In the experiment six tags forming a linear array are placed attached to a container, see fig. 6 to measure the level of water. The container is initially filled by water (case A), and are slowly emptied (case B). The tag array consists of commercial tags Alien ALN-9540. Since they are designed for free-space conditions, the great mismatching that appears when backed requires an increment over $15dB$ on the transmitted power with respect to the required power in air. Such great difference in mismatching conditions between cases A and B implies that under normal conditions the tags attached to the water



(a) Full tank (b) Empty tank

Fig. 6. An array of tags are attached to a container which will gradually change from being filled by water (case A) until it has been completely emptied (case B)

Fig. 7. Picture of the water container with an array of RFID tags

container will work as ON/OFF sensors.

The experimental setup for the measurement is the same than the one used in section III-A2; the transmitting antenna used in this experiment consisted of a ridged horn antenna which was placed at a distance of $20cm$ from an 8 liter container, see fig. 7. Fig. 8 presents the measured response normalized by the response when the container is empty

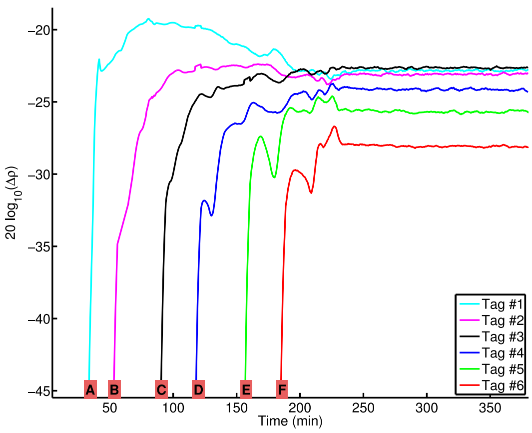


Fig. 8. Measured response of each of the tags as the water level decreases, it shows how the ALN-9540 tags are sequentially activated as the water level decreases, presenting two clear ON/OFF states due to the great mismatch difference between cases A and B

($\frac{\Delta\rho_T}{\Delta\rho_T^{empty}}$). It is observed that as the container is emptied, there is a clear transition between no-answer and a clear answer; on the other hand, it can be observed how the response of the tags once activated does not remain constant, but the magnitude changes due to the variation of the input impedance and thus of $\frac{\tilde{\Delta}\rho_L}{R_T}$. This variation can be used to identify not only a discrete state (such as backed by water or by air), but it could be registered and used as a calibration curve to introduce a finer resolution, [6] between the last responding tag and the first one not-answering. For the case of continuous monitoring, since the evolution of the term $\frac{\tilde{\Delta}\rho_L}{R_T}$ depends on the antenna impedance variation as such, it may be required to have full knowledge of the magnitude and phase of the response to be able to distinguish between *states*, since it is not guaranteed that the curve will be monotonic.

IV. Conclusions

This conference paper has presented the use of multiples tags to exploit the capabilities of indirect sensing with RFID tags, RFID tags and its dependence on the close environment are exploited to obtain information on this environment through the measurement of its response.

The use of commercially available RFID tags on scenarios that present large variations on the permittivity of its neighborhood are likely to arise binary sensing responses, an ON/OFF response. In order to overcome this larger power can be used to ensure activation levels for all cases, which is not always possible. In this cases a larger effort may have to be devoted to the design of the RFID antenna, introducing a new trade-off on its design that takes into account the different permittivities of operation, so that the mismatching for the different cases are more balanced.

At the same time, the design of an array configuration to be used for sensing must take into account the effect of the nearby elements. The design must reduce the coupling between the different tags so that its impact can be reduced to acceptable levels.

Since indirect approaches are based on the relation between the response and the close environment of the RFID IC, it can be used also with enhanced RFID tags, those whose IC include sensing circuitry, and thus expanding its sensing capabilities.

Acknowledgment

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